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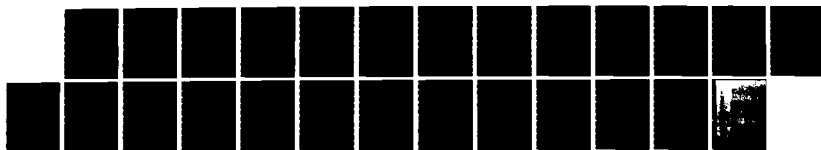
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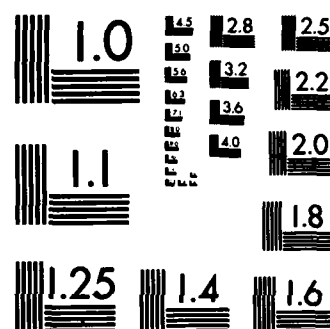
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measurement at each location was typically one day. Over the next several years our intention is to see absolute gravity measurements become both usable and used in the field. To this end, and in the context of cooperative research programs with a number of scientific institutes throughout the world, we are building additional instruments (incorporating further refinements) which are to be used for geodetic, geophysical, geological, and tectonic studies. With these new instruments we expect to improve (perhaps by a factor of two) on the 6-10 μ gal accuracy of our present instrument. Today one can make absolute gravity measurements as accurately as -- possibly even more accurately than -- one can make relative measurements. Given reasonable success with the new instruments in the field, the last years of this century should see absolute gravity measurement mature both as a new geodetic data type and as a useful geophysical tool.

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THE JILA PORTABLE ABSOLUTE GRAVITY APPARATUS

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ABSTRACT

At the Joint Institute for Laboratory Astrophysics, we have developed a new and highly portable absolute gravity apparatus based on the principles of free-fall laser interferometry. A primary concern over the past several years has been the detection, understanding, and elimination of systematic errors. In the Spring of 1982, we used this instrument to carry out a survey at twelve sites in the United States. Over a period of eight weeks, the instrument was driven a distance of nearly 20,000 km to sites in California, New Mexico, Colorado, Wyoming, Maryland, and Massachusetts. The time required to carry out a measurement at each location was typically one day. Over the next several years, our intention is to see absolute gravity measurements become both usable and used in the field. To this end, and in the context of cooperative

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research programs with a number of scientific institutes throughout the world, we are building additional instruments (incorporating further refinements) which are to be used for geodetic, geophysical, geological, and tectonic studies. With these new instruments we expect to improve (perhaps by a factor of two) on the 6-10 μ gal accuracy of our present instrument. Today, one can make absolute gravity measurements as accurately as — possibly even more accurately than — one can make relative measurements. Given reasonable success with the new instruments in the field, the last years of this century should see absolute gravity measurement mature both as a new geodetic data type and as a useful geophysical tool.

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A new, highly accurate, and highly portable absolute gravity apparatus has been designed and developed at the Joint Institute for Laboratory Astrophysics (JILA). In building this new instrument, particular attention was paid to those aspects affecting its field performance. The result, we believe, is a viable and exciting new geophysical tool. The instrument is very small; it can be transported in a small van, and requires about an hour for assembly. A high rate of data acquisition is available: a new drop (measurement) can be made every 2 sec. In developing this instrument, a concerted effort was made to detect and eliminate systematic errors. The results of extensive tests with a prototype apparatus (which served as the basis for Mark Zumberge's Ph.D. thesis [1] and in part as the basis for Bob Rinker's Ph.D. thesis [2]) indicate that the achieved accuracy for g is between six and ten parts in 10^9 . We are now in the process of building six new instruments

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on this prototype) in which we are making a number of modifications aimed at further enhancing the instrument's field usability. We also expect to improve the accuracy obtained with these instruments to between 3 and 5 μ gal. These new instruments, therefore, should provide a sensitivity to vertical motions (e.g., of the Earth's crust) which are as small as 1 or 2 cm.

The principle of the instrument's operation has been discussed in a number of publications [3-7], and is similar to that on which other free-fall gravity instruments have been based [8-27]. We review here the method and in particular our present approach.

Our new apparatus is based on the principles of free-fall laser interferometry (see Fig. 1). In this method one arm of a Michelson interferometer is terminated by a corner cube retroreflector which is allowed to be freely accelerated by the Earth's gravity. The times of occurrence of certain interferometer fringes are measured and then used to determine the acceleration of the falling object. A stabilized laser, the light source, provides the length standard, while an atomic frequency standard provides the time standard.

Two aspects of our new instrument account for its ability to achieve high accuracy without sacrificing small size and, hence, portability. First, a new dropping mechanism has been developed which eliminates several sources of systematic error and makes possible a rapid rate of data acquisition since it minimizes the resetting time required between drops. Second, a new type of long-period isolation device [2,28] is used to greatly decrease the instrument's sensitivity to ground vibrations. This avoids the large drop-to-drop scatter that would otherwise result from our comparatively short dropping length (20 cm) — a consequence of the instrument's small size.

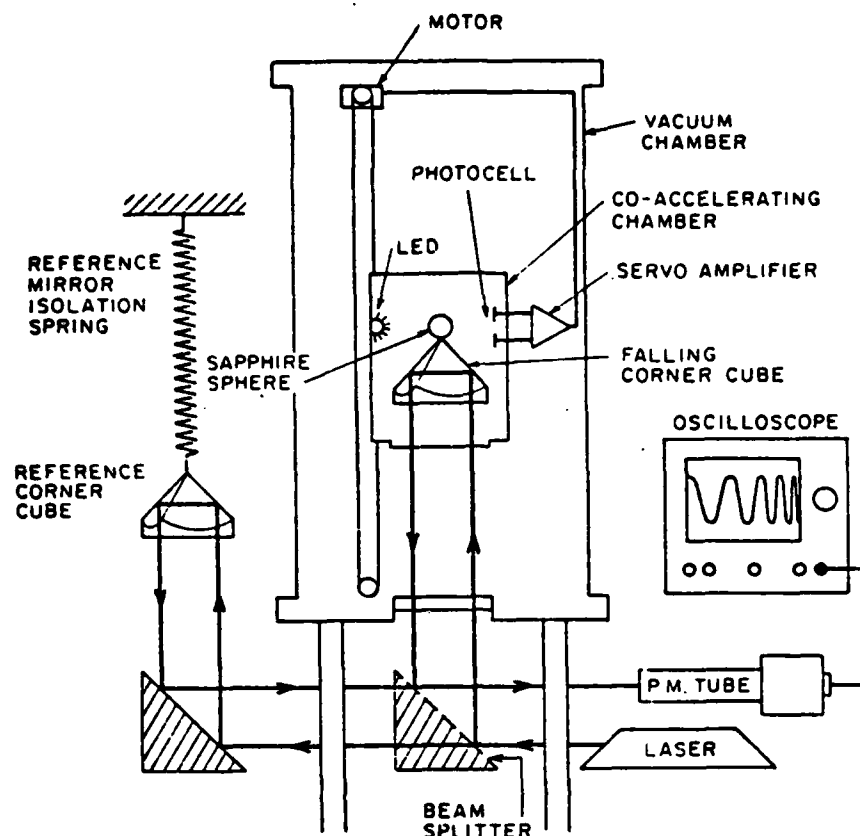


Fig. 1. Schematic of absolute gravity apparatus.

In the free fall method, air drag makes it impossible to approach any reasonable accuracy without dropping the corner cube in a vacuum. In the JILA instrument, the dropped object is contained in a servo-controlled motor-driven drag-free evacuated dropping chamber which moves inside the main vacuum system. This dropping chamber effects the release and then tracks the falling object — without touching it — during the measurement, and at the end of the measurement gently arrests the dropped object's free fall. The result is that the object falls with the residual gas molecules rather than through them.

Figure 2 is a schematic representation of our prototype dropping chamber. The dropped object rests in kinematic mounts in a chamber that can be driven along vertical guide rails by a thin stainless steel belt which is connected to a dc motor. The position of the dropped object relative to this drag-free chamber is measured by focusing light from a light-emitting diode, through a lens attached to the dropped object, onto a position-sensitive photodetector. The error signal thus derived controls the motor that accelerates the chamber downward which results in the dropped object freely floating inside. Near the bottom of the drop, the chamber is first servoed to gently arrest the dropped

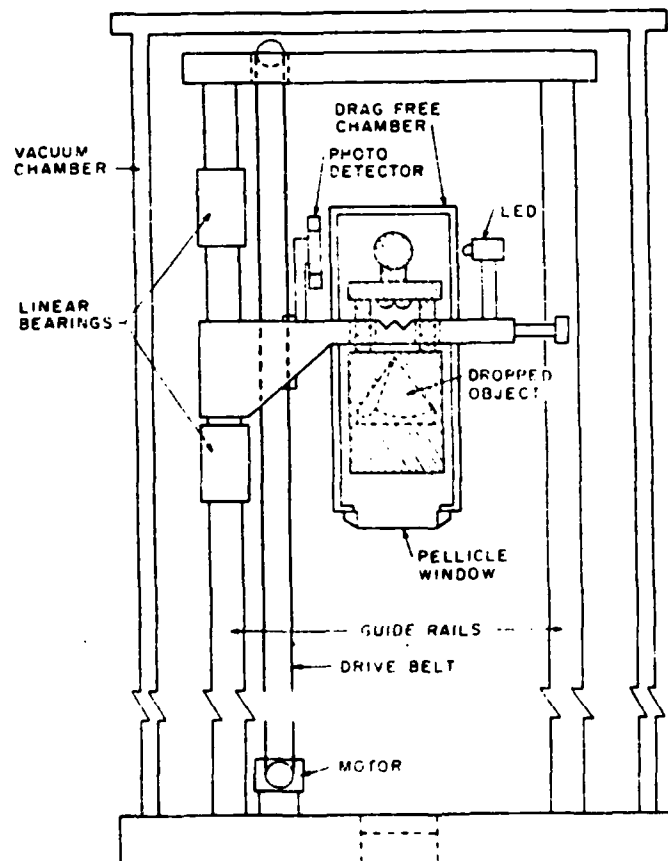


Fig. 2. Schematic of dropping system.

object's fall, and then used to return the dropped object to the top of the track for the next measurement. This rapid turnaround capability is primarily responsible for the system's ability to acquire data at a very high rate.

The falling chamber also serves to remove other nongravitational forces. It provides an electrically conducting shell to completely surround the dropped object so that external electrostatic fields do not affect the measurement. Also, the purely mechanical character of the release makes it unnecessary to have any sort of magnetic support or release mechanism that might subsequently result in an unwanted magnetic force.

If one is to achieve a few parts in 10^9 accuracy in g , an effective method must be found to isolate either the entire system or the reference cube (hung vertically so that vertical motion of the base shortens both arms equally). The need for this isolation stems from the fact that, during a measurement, the dropped cube is completely isolated during its free fall from the Earth's micro-seismic motion and other man-made noise. The reference corner cube (in the other arm of the interferometer), however, is not. In the past, a stable spring systems have been used such as those employed in commercially available long-period vertical seismographs. These systems, however, are somewhat awkward to adjust and suffer from internal (violin-string) modes in the main system spring.

We electronically terminate a tractable length of spring (i.e., 30 cm) so that it behaves exactly as if it were, for example, 1 km long. The mass on the end oscillates up and down with a period of 60 sec ($\nu = 0.017$ Hz) and therefore is isolated for all periods shorter than this. To understand this electronically generated "super spring," imagine you have a 1 kg mass hanging on the end of a weak coil spring which extends 1 km vertically. This mass will

oscillate up and down (with a period of 60 sec) and as it does, the coils of the spring will oscillate up and down also. The coils very near the mass will have an amplitude nearly equal to the amplitude of the mass and the coils that are far away from the mass will have an amplitude less than that of the mass. In fact the coils near the top will scarcely move at all. Now if one were to grasp the spring 30 cm above the mass and move that point on the spring just as it moved when the lower portion was in free oscillation, the motion of the mass would remain unchanged. Having done this, one could then cut off the top of the spring and be left with a 30 cm long spring that has the same resonance frequency, and behaves in all ways exactly as a spring 1 km long. In our "super spring" we use a servo system to generate such a virtual point of suspension.

Figure 3 is a schematic drawing of this system. The two side springs supply the force to support a bracket on which a mass is attached by a central spring; this bracket is free to move in a vertical direction. The light from the LED is focused by the sapphire ball onto a split photodiode. The outputs from the two halves of this diode are amplified and differenced, producing an analog signal that is proportional to the displacement of the weight. This signal is processed by a servocompensated amplifier which drives a loud speaker voice coil. This coil then supplies the needed force on the bracket to cause it to track the motion of the bottom weight. Since the top of the spring is attached to the bracket, the top moves with nearly the same amplitude as the bottom. The degree of tracking is determined by the gain setting of the servo system and this in turn sets the effective length of the spring and thereby the achieved period. While we can easily achieve periods in the range of 10 to 100 sec, we normally use a period of about 50 sec.

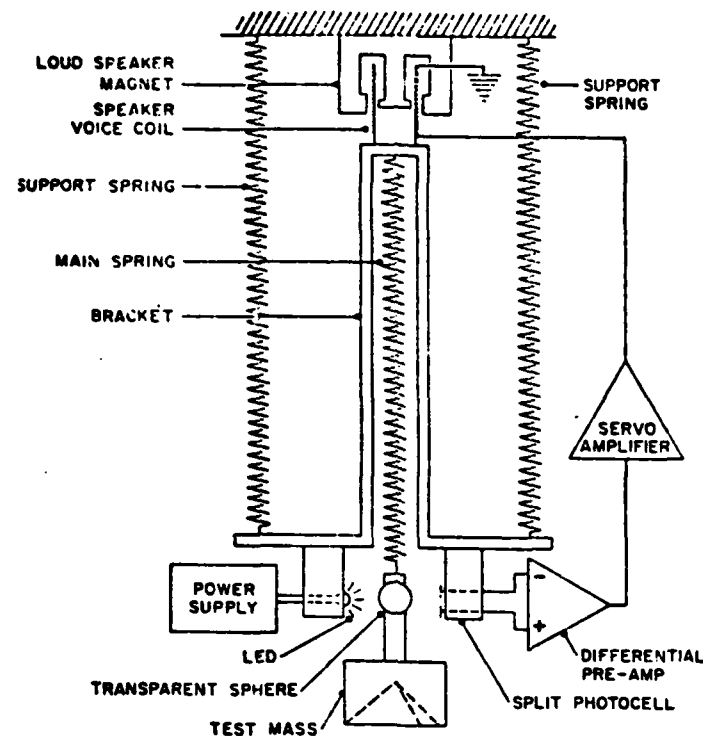


Fig. 3. The "super spring."

In order to test the super spring concept, we constructed a "shake table" on which we could place the spring. The table surface, driven by a system of levers and a speaker magnet-voice coil system, is constrained so as to tilt less than one arcsecond for vertical motions of the order of 5×10^{-3} cm. A LED photodiode position detector was used to monitor the table motion. The isolation measurements were made using a spectrum analyzer whose internal noise source was used to drive the table. The output from the table's position detector and the position of the test mass with respect to the floor ("inertial space") were applied to the two inputs of the spectrum analyzer which computed the transfer function. Figure 4 is an example of such a

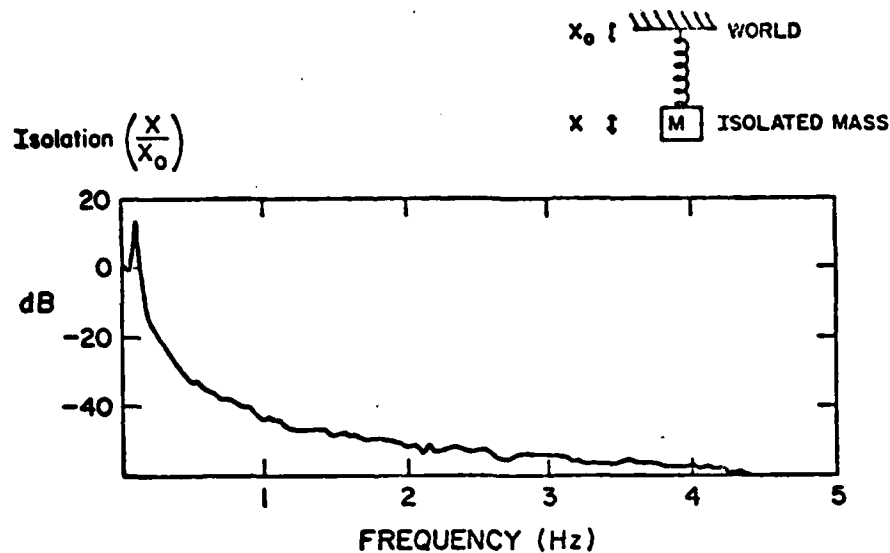


Fig. 4. Transfer function obtained during "shake table" testing of super spring.

transfer function. This particular one was taken with the spring period set at 12 sec (shorter than usual so that the 1/12 Hz resonance can be seen).

Further evidence that the spring does indeed isolate is obtained when the test mass is used to hold the reference corner cube in the gravimeter. Figure 5 shows two histograms of 150 "g" measurements each. The use of the spring is seen to reduce the scatter by a factor of 20.

Figure 6 is a photograph of our prototype apparatus. The dropping mechanism is inside a vacuum chamber which is supported by three folding legs. Beneath this is a base that supports the long-period isolation spring and contains the associated optical components that comprise the interferometer. The electronics fit nicely in two packing cases.

Figure 7 illustrates results from two days of continuous operation at about 70% of the maximum possible data acquisition rate. The tidal effects of

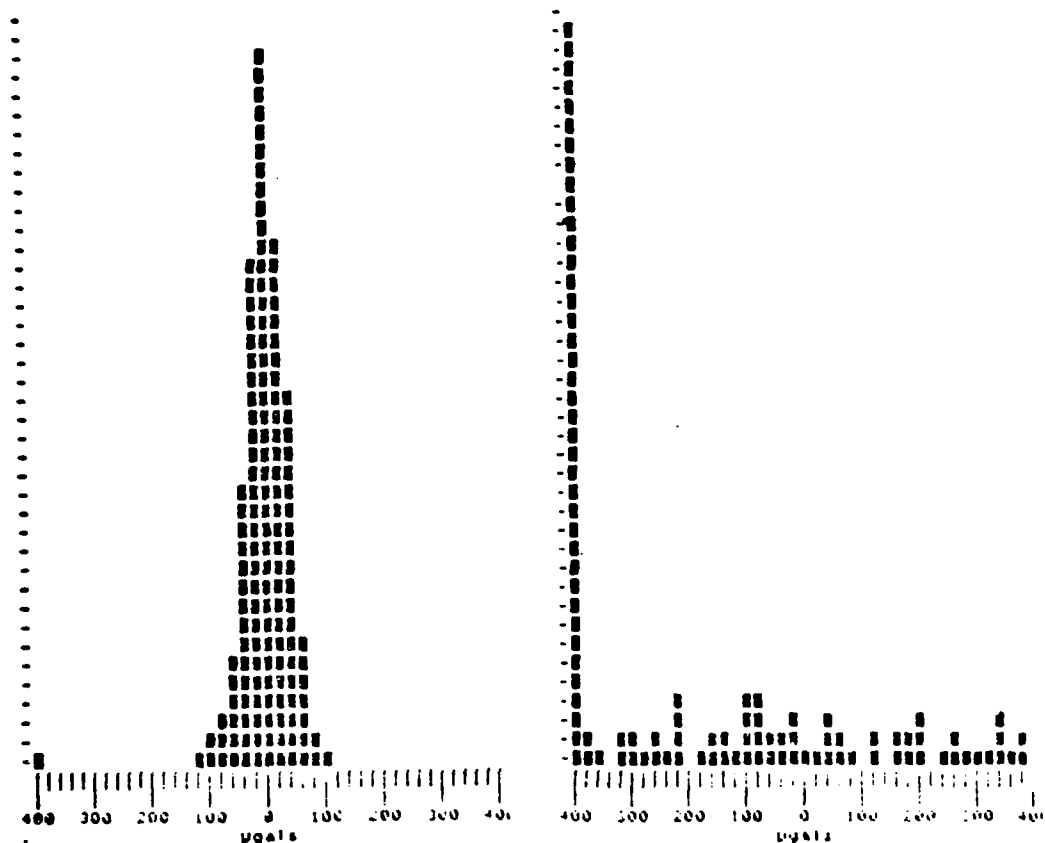


Fig. 5. Histogram of measurements of the gravitational acceleration of g with and without super spring isolated reference corner cube.

the sun and moon can easily be seen. The solid line is the theoretical tides calculated without the inclusion of any ocean loading effects (which are small in Boulder). If we subtract the theoretical tides, we obtain an rms deviation of about 6 μgal for the means of sets of 150 drops. Removal of the theoretical variation due to changes in barometric pressure did not reduce the rms deviation. No attempt was made to correct for other meteorological effects.

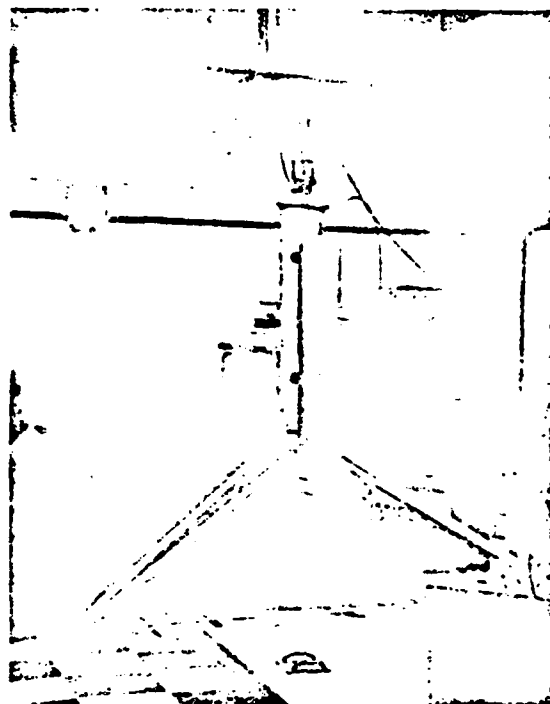


Fig. 6. Photograph of apparatus.

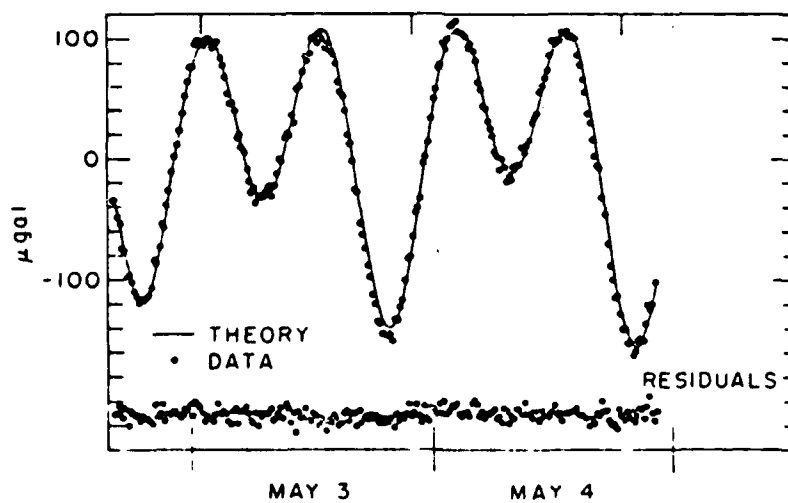


Fig. 7. Gravity tide.

The fundamental problem in measurements of this sort is the recognition and elimination of systematic error sources. Table 1 gives a concise summary of the sources of error that we have recognized and considered to date.

High repeatability of a measurement (e.g., the precision) is unfortunately not always an indication of the accuracy; it is, however, a necessary condition. A rather detailed discussion of the question of accuracy has been published elsewhere [1,6]. For a year-long period, during which many tests and evaluations were made involving both disassembly of and modifications to the instrument (including a trip with the instrument to Paris to participate in an international intercomparison of gravity meters), the rms deviation in g as measured in our JILA laboratory amounted to about $10 \mu\text{gal}$ (Fig. 8). We are unable to attribute this variation to any specific effect, although we suspect that some part of it may be related to changes in ground water content around and under our sub-basement laboratory.

Table 1. Known systematic errors

Source	Error
Differential Pressure	$1.0 \mu\text{gal}$
Differential Temperature	1.0
Magnetic Field Gradient	0.5
Electrostatics	1.2
Attraction of Apparatus	0.5
Vertical Reference	0.8
Optical Path Changes	2.8
Laser Wavelength	1.0
Rotation	1.0
Translation	1.0
Floor Recoil	1.0
Phase Shift	1.0
Frequency Standard	0.5
rms Total	$4.2 \mu\text{gal}$

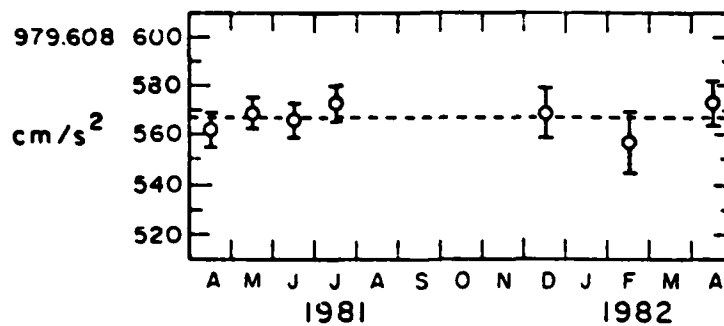


Fig. 8. Absolute gravity measurements at JILA over a one-year period. One vertical division is 10^{-7} m/sec² (10 μ gal).

In 1982 we completed an absolute gravity survey at twelve sites in the U.S. Eight sites had been previously occupied by other absolute instruments and four were new sites chosen because they were near locations in which other measurements relevant to the study of geodynamics have been made. Over a period of eight weeks, the instrument was driven a total distance of nearly 20,000 km to sites in California, New Mexico, Colorado, Wyoming, Maryland and Massachusetts. A measurement accuracy of around 1×10^{-7} m/sec² (10 μ gal) is believed to have been obtained at all but one of these sites. At one site, floor motions as well as other unfavorable characteristics of the surroundings resulted in a measurement uncertainty at least an order of magnitude larger than obtained elsewhere.

At most of the twelve sites, the entire operation of unloading, assembling the instrument, acquiring the data, disassembling and reloading required less than one day. The vacuum chamber was pumped continuously, even during transport in a small truck. This eliminated the pump-down time that would otherwise have been necessary preceding each measurement. At three sites,

mechanical problems inside the dropping chamber required some attention, and as a result the vacuum was lost. This usually meant an overnight delay — to achieve a good vacuum — after the problem was corrected.

When no difficulties were encountered, the operation proceeded smoothly and rapidly. The time needed to get the instrument set up and running was two hours. Although gravity data were available immediately following the instrument's assembly, they were generally rejected because of known instrumental biases that can result from temperature transients. To insure quality gravity measurements the instrument had to remain passive for an hour or so after its initial setup and testing. During this time, the laser, the long-period isolator, and the pressure in the vacuum chamber equilibrated with the new temperature environment.

The period over which actual measurements were taken varied among the sites from several hours to as long as one day. Since a data set of 150 drops can be taken in ten minutes, the statistical uncertainty is outweighed by systematic effects after a few hours of measurements. Disassembly and reloading required approximately one hour, as did the transfer of the absolute value from the measurement height to the floor using a relative gravimeter. Eight of the twelve sites had been previously occupied by the Air Force Geophysics Laboratory (before the occurrence of that instrument's gravity offset) or the Istituto de Metrologia "G. Colonnetti" absolute gravimeters. Five of these sites were occupied by all three absolute gravimeters. Details of the results obtained are given elsewhere [29]. Since the reported accuracy from all three instruments is typically 1×10^{-7} m/sec² (10 µgal), most of the intercomparisons should agree to about 1.4×10^{-7} m/sec² (14 µgal). This is true at some sites, but not at others. Some of the differences could be due to real gravity changes, because

simultaneous measurements were not made. The method of transferring the measured values to a common reference height of one meter could also contribute slightly to the differences. It is more likely, however, that the discrepancies are due to unrecognized systematic errors in one or more of the instruments. Clearly, further observations and more intercomparisons are needed.

Now that we have a successfully working, field-usable instrument — an instrument that exploits available technology as well as incorporates our own research from the past 25 years — we plan to insure that this new type of gravity instrument is widely used and field tested in as many different geophysical settings as possible. To this end, we are in the process of building six new instruments (see Fig. 9). One of these will remain at JILA and will be used chiefly for continued research and development. The other five are being built for and in connection with cooperative scientific programs which we are establishing with the Division of Gravity, Earth Physics Branch, Department of Energy, Mines, and Resources in Ottawa, Canada; the Institute of Earth Measurement in Hannover, W. Germany; the National Geodetic Survey in Washington, DC; the Institute for Meteorology and Geophysics in Vienna, Austria; and the Finnish Geodetic Institute in Helsinki. In addition (in the context of a protocol agreement between the NBS and the National Institute for Metrology in Beijing, China), we are helping NIM to build a copy of our new instrument in China. We are making a number of significant changes in the prototype design to either improve the instrumental accuracy or enhance the instrument's field performance. In particular, the process of transforming a "theses" instrument to one which can be used and maintained in a routine fashion involves some effort. For example, a multitude of hand-wired circuit boards have been condensed (in

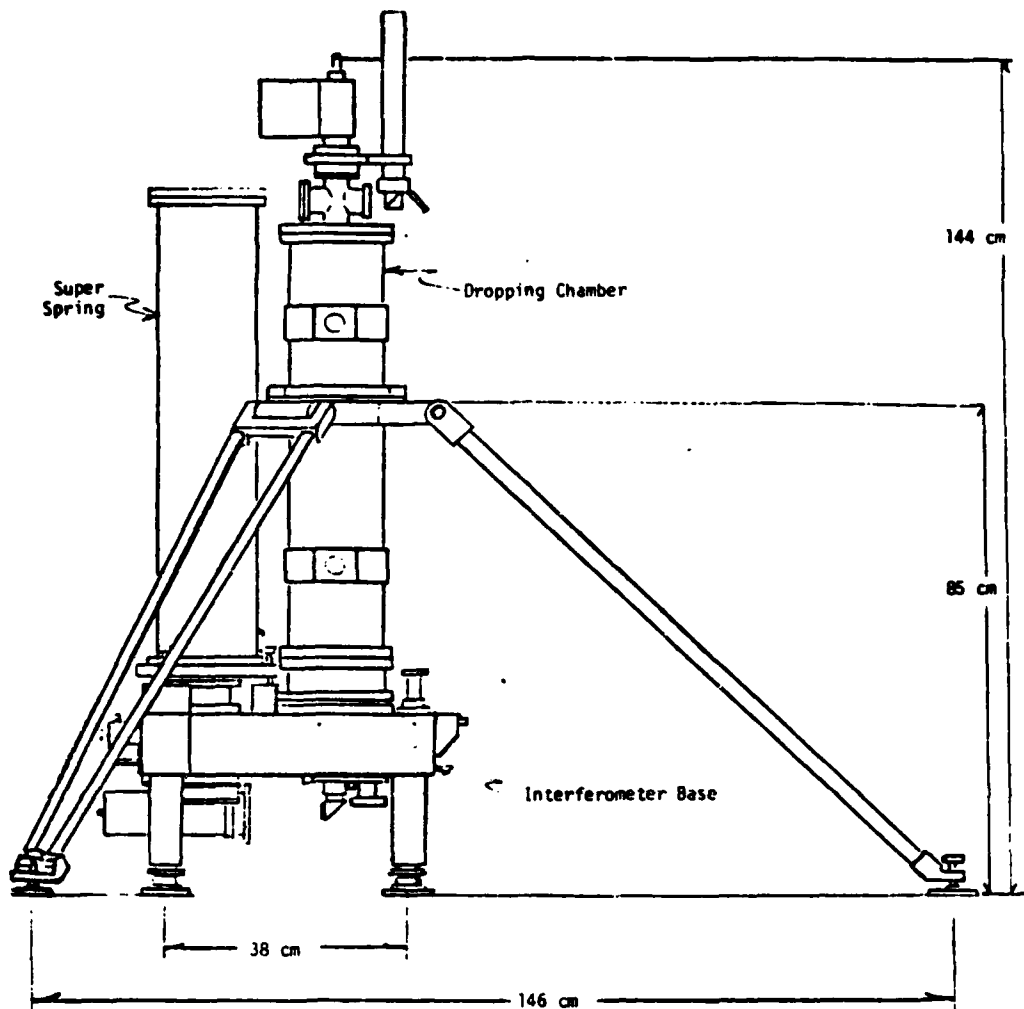


Fig. 9. Line drawing of new JILA instruments.

space) and transformed to printed circuit boards. Set-screw-maintained shaft couplings (our experience has been that they always eventually work loose) have been replaced with collet-type couplings which are considerably more difficult — and therefore more expensive — to fabricate but which we believe will prove much more satisfactory in terms of long-term and field reliability. We have redesigned and rearranged the optical system so that it is easier to

work on, and much faster to align the laser beam vertically in the free-fall arm of the interferometer. What once took about 15 minutes to accomplish when setting up the instrument can now be done in much less time. We have also recognized the rapidly changing computer technology and have configured the system to take advantage of one of the most recent machines, replacing an older style computer (and its somewhat slower performance) that was used in the prototype instrument. In fabricating the new instruments, the design philosophy has been to produce individual components from single pieces of metal rather than to fabricate them out of several pieces — thus increasing both their rigidity and their mechanical integrity.

Certain changes have also been made that decrease the scatter and/or increase the achieved accuracy. For example, to reduce the drop-to-drop scatter, we have substantially increased the tightness of the servo-lock on the position of release at the top, and by so doing reduced the starting height uncertainty to the order of a small fraction of a millimeter. Perhaps the most fundamental change has been the elimination of the pellicular window from the bottom of the drag-free chamber; its "shielding" function has been replaced by collimating tubes (see Fig. 10) which will serve to restrict (to an acceptable level) the number of molecules that make a direct vacuum-wall-to-the-dropped-object uninterrupted transit. The reason for this is clear if you look at the error budget that we developed for the prototype instrument. You will note that it contains one dominant term — the path-difference error associated with the pellicle's (inevitable) wedge and the coupling of this wedge into the free-fall path length as the carriage accelerates downward and experiences small but nonetheless real sidewise and systematic displacements due to the imperfect straightness of the

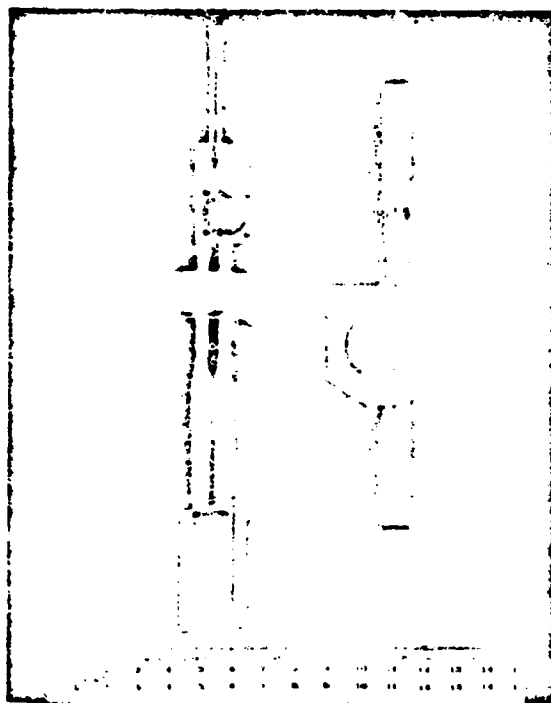


Fig. 10. New, drag-free chamber.

guide rod. By replacing this wedge with appropriately sized open tubes, we can completely eliminate this single dominant systematic error term and thereby reduce our error budget from the present $4.2 \mu\text{gal}$ to $3 \mu\text{gal}$. (The single tube seen at the top makes possible a fairly simple locking mechanism to cage the dropped object during transit.)

We have not (and indeed in the space available could not have) mentioned all of the various refinements we are incorporating into these new instruments; nevertheless we have tried to give some idea of the types of changes we are making and the motivations for them. Even our new instruments, we feel, should still be thought of as laboratory (and field) prototypes rather than as commer-

cial instruments, even though — to the best of our abilities and based on our experiences with the prototype JILA absolute gravimeter — we are trying to correct and improve both performance and field adaptability. Any "next group" of instruments — if there is sufficient interest — would, however, need to be made commercially.

What about the future for absolute gravity measurements? In 1963, one of us (JEF), attended his first IUGG meeting (in Berkeley) and talked about his recently completed Ph.D. thesis, "An Absolute Interferometric Determination of the Acceleration of Gravity," a measurement which was good to 7 parts in 10^7 and which used white light fringes in connection with optical interferometry. After his talk, he remembers walking up to Dr. LaCoste and asking him if he thought that absolute gravity instruments would someday be used — at least for some purposes — instead of relative gravimeters. Dr. LaCoste replied that at least for the time being, he wasn't worried. Twenty years later, what answer might be given to the same question at this Hamburg IUGG meeting?

Today, gravimeters are being increasingly used as reconnaissance tools in geodynamic research. Because gravity data are sensitive to both vertical height and the subsurface mass distribution, they can provide a powerful and unique type of information. Vertical crustal movements — which have characteristic rates of centimeters per year — will require a precision of 3-10 μgal ($1 \mu\text{gal} = 10^{-6} \text{ cm/sec}^{-2}$) in order for gravity measurements to be useful on time scales of one or two years. Because even the best portable spring-type gravimeters have serious difficulties with tares and long-term drifts at this level of sensitivity, the value of absolute gravimeters with accuracies of several μgal for this type of work is obvious. Today one can make absolute measurements as

accurately — possibly even more accurately — than one can make relative measurements. Further, although absolute instruments are more complicated to operate, the time required to make a measurement at a particular site is comparable to that for a relative instrument when one includes the back-and-forth ties that must be made when using a relative gravimeter. And although the size of an absolute instrument is considerably larger than that of a relative gravity meter, perhaps the important thing to note is that either one can easily fit into a small truck or van.

While there remains work yet to be done, one should not fail to be impressed with the extraordinary progress that has been made over the past several decades by workers in the field. Today's answer to the question posed in 1963 must surely be that if today's easily portable new instruments prove to be usable and reliable in the field without sacrificing their laboratory-obtained levels of accuracy, then, given continued interest and support, the last 20 years of this century should see absolute gravity mature as a useful adjunct to, and in some cases a replacement for, relative gravity both as a new geodetic data type and a useful geophysical tool.

Acknowledgments

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